



Precision-guided surgical navigation system using laser guidance and 3D autostereoscopic image overlay

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ABSTRACT

This paper describes a precision-guided surgical navigation system for minimally invasive surgery. The system combines a laser guidance technique with a three-dimensional (3D) autostereoscopic image overlay technique. Images of surgical anatomic structures superimposed onto the patient are created by employing an animated imaging method called integral videography (IV), which can display geometrically accurate 3D autostereoscopic images and reproduce motion parallax without the need for special viewing or tracking devices. To improve the placement accuracy of surgical instruments, we integrated an image overlay system with a laser guidance system for alignment of the surgical instrument and better visualization of patient's internal structure. We fabricated a laser guidance device and mounted it on an IV image overlay device. Experimental evaluations showed that the system could guide a linear surgical instrument toward a target with an average error of 2.48 mm and standard deviation of 1.76 mm. Further improvement to the design of the laser guidance device and the patient-image registration procedure of the IV image overlay will make this system practical; its use would increase surgical accuracy and reduce invasiveness.

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1. Introduction

Image-guided surgery is a means of navigation that guides the surgeon by indicating the location of a tracking device through a set of cross-sectional images, for example, X-ray computed tomography (CT) and/or magnetic resonance (MR) images, or three-dimensional (3D) anatomical models reconstructed from such images. By localizing the target and the critical lesion that should be avoided, surgical navigation helps to achieve effective and safe surgery while minimizing the invasiveness of the surgery [1].

In conventional surgical operations, the display of the surgical navigation system is often placed in a nonsterile field away from the surgeon. The consequent hand–eye coordination problem forces the surgeon to take extra steps to match the guidance information on the display with the actual anatomy of the patient [2], which can be time consuming, especially when the target is small and deeply located. The problem is a possible interruption in the surgical flow

[3]. To overcome this problem, several research groups have developed techniques that merge images into real-world views in a more natural and unconstrained manner. These techniques involve an image overlay that visually merges a computer-generated anatomical model, reconstructed from medical images, with the patient's body [4–6]. Another example is the use of augmented reality visualization with microscopes or endoscopes in image-guided surgery [7,8].

Most studies on augmented reality in surgical environments have focused on the use of virtual reality operative microscopes, head-mounted displays (HMD), and semi-transparent mirrors. These image-overlay studies focused on how to overlay pre-/intra-operative images on the patient. Few came close to resolving the problem of intuitively guiding surgical instruments. Certain surgical treatments such as those of orthopedic surgery, requires high position and orientation accuracy when the surgical tools are inserted into the patient. For example, during knee joint surgery, the surgeon needs to identify both the surgical area and the insertion path for tunneling or drilling.

Researchers in the 1990s introduced the use of lasers for surgical instrument guidance. Miaux et al. developed a laser guidance system for CT-guided procedures [9], and Pereles et al. introduced a laser guidance system for percutaneous musculoskeletal proce-

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dures [10,11]. These systems enable needle placement to be more accurate, thus saving time compared to a freehand approach by minimizing the need for repositioning. The desired puncture angle is defined by the laser beam. The needle is aligned with the beam, and throughout the procedure, the laser dot should shine at the hub of the needle to indicate correct alignment.

Sasama et al. developed a laser guidance system that was monolithically integrated with an optical tracker [12,13]. The laser beams are projected onto the surgical field so that the surgeon can obtain guidance information directly. Glossop et al. used scanned infrared and visible lasers to project computer generated information onto the patient by moving a laser beam in arbitrary directions by means of controlled mirrors [14]. These systems still cannot provide intuitive visualization of complex anatomical structures of inside the patient's body. Moreover, their devices are located at a distance from the surgical area and sometimes cause interruptions during the operation.

To improve the safety and accuracy of surgical treatments, especially those using linear surgical tools for puncturing and drilling, we developed a 3D autostereoscopic image overlay system integrated with a laser guidance device. Two lasers are reflected by mirrors, and their projection directions are controlled by motors; this arrangement gives more freedom to the laser guidance beams. The combination of image overlay and laser guidance enables both visualization of the patient and guidance for the surgical instrument.

2. Materials and methods

2.1. Laser guidance and procedure

The laser guidance system includes two lasers, which project individual laser planes that intersected as a line in space (Fig. 1). The plane of laser light is produced by a high-quality compact line-laser module. The laser shooter modules are fixed to motors on a stand. The orientation of the projected laser plane can be adjusted by rotation of the motor. Furthermore, we use mirrors to reflect the beams to the target area. The angles of the mirrors are also controlled by motors so that the beams can be adjusted to the required position and direction onto the target. Two laser-beam planes are projected onto the surgical area, and the projection directions are controlled by the navigation system on a PC. The rotation angles of the motors are limited so that the lasers do not project outside of the required area.

The intersection line generated by the laser planes is used to guide the insertion path of a linear surgical instrument. Fig. 2 shows the procedure for aligning the surgical instrument.

- (1) Two laser planes cross on the surgical area (Fig. 2a). The point of intersection of these planes on the target area is determined by using the calibration and patient registration method described in Sections 2.4 and 2.5.
- (2) Move the tip of the surgical instrument to the crossing point on the target area (Fig. 2b). The position of the crossing point should be calculated according to the 3D shape of the anatomical structure.
- (3) Rotate the surgical instrument around the crossing point and align it to the insertion path (Fig. 2c). Adjust the orientation of the surgical instrument till the laser beam shines on top of it. The proper orientation can be determined by putting a coaxial point on the tail of the surgical instrument or by putting parallel straight lines on the cylindrical surface of it (Fig. 2d).
- (4) Stabilize the surgical instrument after obtaining the surgical path by the aligning it with the insertion point and orientation. Confirm the correct position by repeatedly scanning with the surgical instrument, if necessary.

2.2. IV autostereoscopic image overlay

The autostereoscopic image overlay technique can be integrated into a surgical navigation system. This technique superimposes an actual 3D image onto the patient from the perspective of the surgeon by using a half-silvered mirror. The autostereoscopic image is generated by using a version of integral videography (IV) [15,16], which is an animated extension of the integral photography [17].

The IV display we developed consists of a high-resolution 2-D LCD with a microconvex lens array. The computer-generated images of the anatomical object are rendered behind the lens array. The source image shown on the display is generated from the 3D data by high-speed IV rendering. Any kind of 3D data source, such as MRI and CT images, can be processed. Each point shown in the 3D space is reconstructed at the same position as the actual object through the convergence of rays from the pixels of the element images on the computer display after they pass through the lenses of array. The surgeon can see any point on the display from various directions, as if it were in 3D space. Each point appears as a different light source, and a 3D object is thus constructed as an assembly of reconstructed light sources [15]. Since the element images are in the focal plane of the lens, only one pixel can be observed from each lens. The observed lateral resolution of the IV image is proportional to the number of lenses. On the other hand, since viewpoints equal to the number of the pixels are covered by one lens, the vertical resolution is determined by the pixel number. The quality of the IV image depends primarily on the pixel density of the 2-D display and the lens pitch of the array. To improve image quality, both the pixel pitch

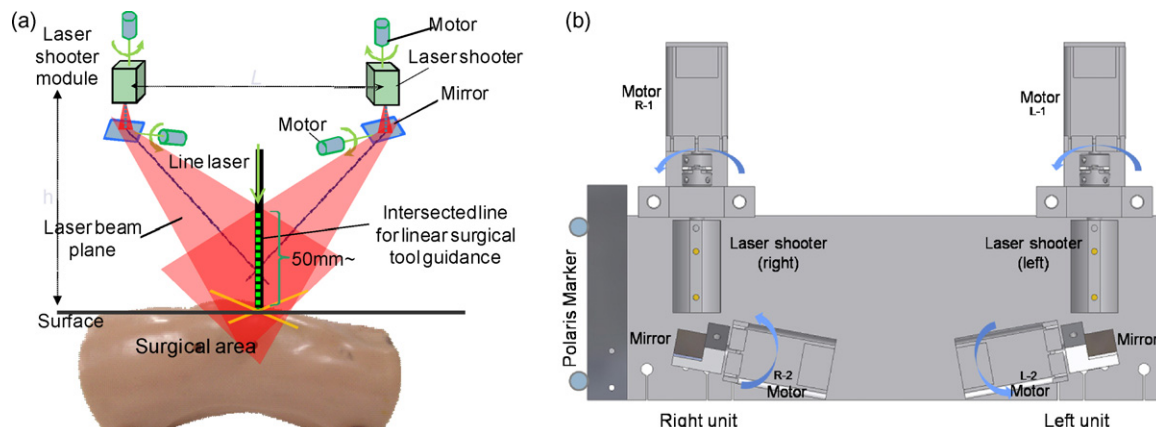


Fig. 1. (a) Laser guidance by using two intersecting laser beam planes. (b) Configuration of laser guidance device.

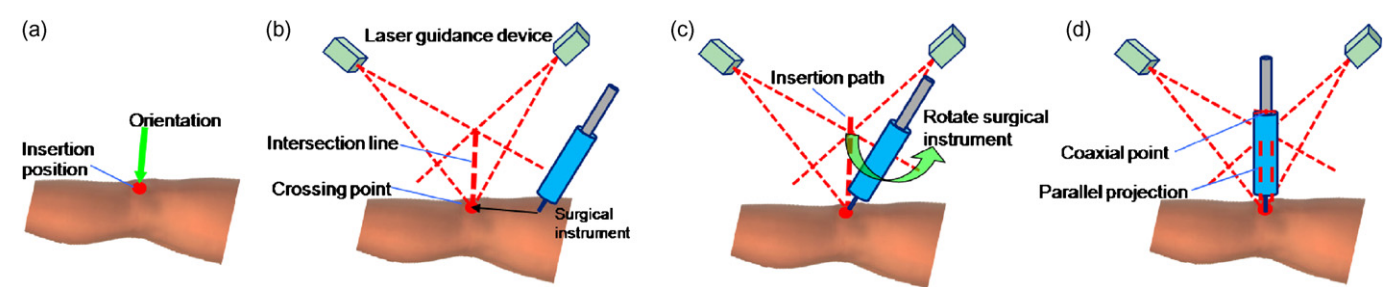


Fig. 2. Procedure of surgical instrument alignment: (a) target in surgical area; (b) move the tip of surgical instrument to the insertion point; (c) rotate surgical instrument and adjust its orientation; (d) align surgical instrument to the target orientation by using coaxial point or parallel projection lines.

of the element images and the lens pitch must be made smaller. Furthermore, the error between the lens pitch and the width of the element image causes the deformation that may significantly affect the perceived depth perception of deep locations. Pixels adjustment and image correction o must be performed before the IV display is used.

The main elements of the overlay system include the intuitive 3D image on the IV display, a half-silvered mirror, a reflected spatial 3D image, and a supporting stage [15]. A surgeon observes the operating field directly by eye during an operation. To ensure smooth operation, the surgeon must be able to identify the target object, avoid specific areas (critical areas), and respond to intra-operative information when it is presented.

2.3. System of IV image overlay with laser guidance

The surgical navigation system consists of the IV display, the laser guidance device, 3D data source collection equipment, an optical position tracking device (POLARIS, Northern Digital Inc., Waterloo, Ontario, Canada) and a personal computer, as shown in Fig. 3. The laser guidance device is mounted at the bottom of the IV image-overlay device. The distance between the laser shooter and the patient is about 30 cm. The projection direction of the laser plane is adjusted by a motor rotating the mirror axis. The optical position tracking system is used for both calibration of the laser guidance device and registration of the IV-image to patient. To project the laser beams at the proper position and orientation, we

calibrate the position and orientation of the intersection line and calculate the relationship between the reflection direction of the mirror and the rotation of the motor. For this, a needle or surgical instrument is inserted superficially into the point of entry of the patient and aligned to the intersection line of the laser beam planes.

Fig. 4 shows a flowchart illustrating the IV image overlay with the laser guidance. Performing an image-guided surgery involves two important steps: (1) Initialize the IV image overlay device and register the image to the patient. Using this image overlay, the surgeon can see through the patient's body intuitively. (2) Initialize the laser guidance device and control the laser beams to corresponding directions. With this laser guidance, the surgeon can visualize the insertion position and path of the surgical instrument directly. If intra-operative information of patient and surgical instrument is updated, we will perform the IV image registration and corresponding laser guidance again.

2.4. Calibration of laser guidance device

The projected directions and reflected angles of the laser beam planes are calculated on the basis of the required position and orientation of the surgical instrument. The laser shooter is in a sheath firmly connected to one of the motors. The procedure of adjusting the axis of the laser shooter and the direction of the projected line laser is somewhat complicated. The calibration process consists of the following steps.

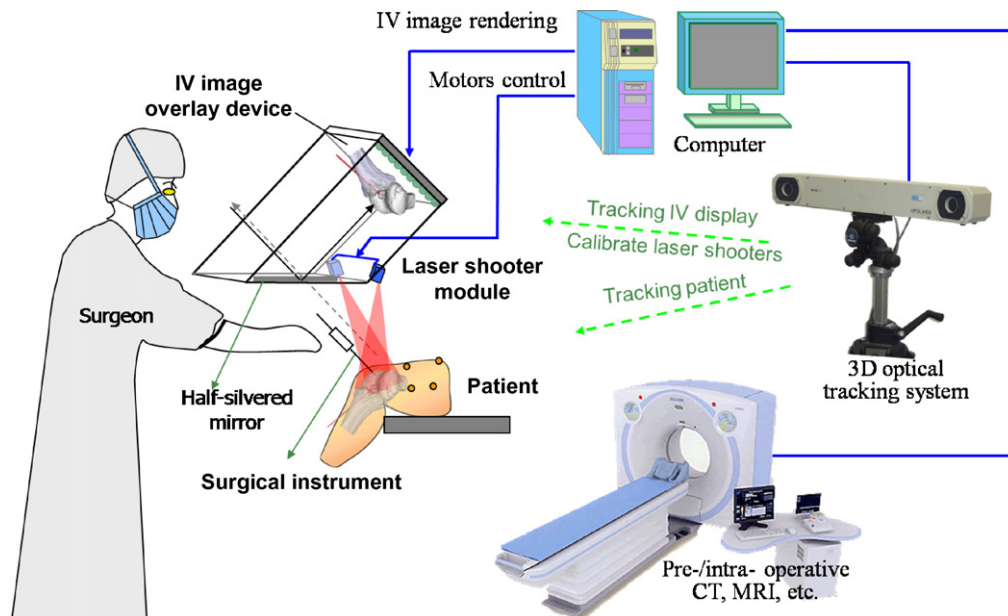


Fig. 3. System configuration of IV image overlay with laser guidance.

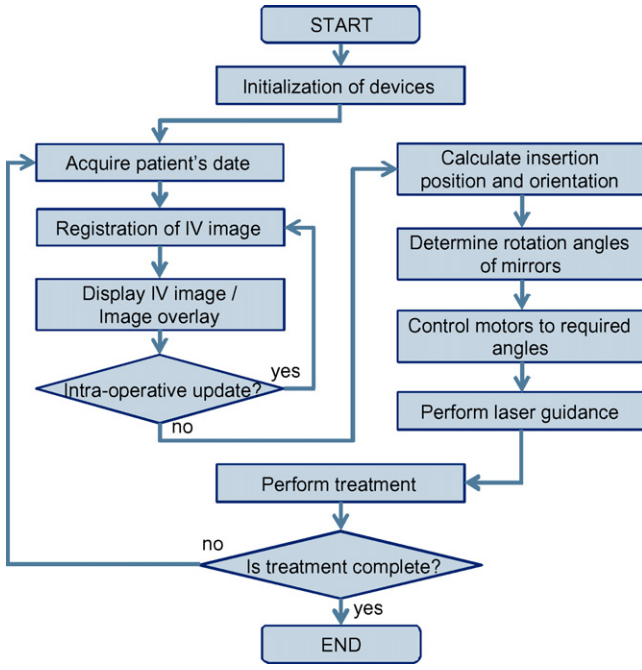


Fig. 4. Procedure of IV image overlay with laser guidance.

- (1) Adjust the direction of the laser shooter to make its axis parallel to the axis of the motor. For this, we insert two mounts into the sheath and adjust the position of the laser shooter. This alignment is laborious and does not yield precise alignments. A software based calibration method is being developed to correct any misalignment of the axis of the laser shooter.
- (2) Calibrate the movements of the motors with angles of the mirrors. Calculate the relationship between the reflected laser plane and the angle of the mirrors so that the rotation angles can be thus controlled by the stepping motors.
- (3) Calibrate the position and orientation of the intersection line of the two laser beam planes. A set of test laser beams are projected onto a plate in different directions. The 3D spatial positions of the projected laser beams are measured with the optical tracking device. Accordingly, the relationship between the projected laser beam plane and the rotation angles of the mirror and the motors can be determined.

The laser guidance devices are fixed in the IV overlay device, which can be also tracked by the same optical tracking device. Thus we can calculate the transformation matrix between the original laser plane and the optical tracking device.

The rotation angles of the mirrors and the laser shooters are determined as follows. The coordinates of the system are shown in Fig. 5. First, we consider the right-side laser module. We set rotations that represent a counterclockwise rotation of angle α_1 around the axis of motor R-1 (the motor axis is parallel to the x-axis). The normal direction of the projected laser beam plane becomes $\vec{n}_1 = R_x(\alpha_1)\vec{n}_0$, where

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{bmatrix}$$

Given a unit vector $\vec{u} = (u_x, u_y, u_z)$, the matrix for a counterclockwise rotation through an angle of θ about an axis the direction of \vec{u}

is $R(\vec{u}, \theta) = P + (I - P) \cos \theta + Q \sin \theta$; where

$$P = \begin{bmatrix} u_x^2 & u_x u_y & u_x u_z \\ u_x u_y & u_y^2 & u_y u_z \\ u_x u_z & u_y u_z & u_z^2 \end{bmatrix} = \vec{u} \vec{u}^T, \quad Q = \begin{bmatrix} 0 & -u_z & u_y \\ u_z & 0 & -u_x \\ -u_y & u_x & 0 \end{bmatrix},$$

and I is a 3×3 identity matrix.

Let the original normal vector of the mirror be \vec{n}_{m0} , and the direction of the rotation axis be \vec{n}_{r0} . We first rotate the axis of Motor R-2 (on the mirror plane) clockwise through an angle ϕ_1 around the z-axis. The direction of the axis of Motor R-2 is given by $\vec{n}_r = R_z(\phi_1)\vec{n}_{r0}$, where

$$R_z(\theta) = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

After rotating the mirror through an angle of β_1 around the axis of Motor R-2, the normal vector of the mirror changes to $\vec{n}_m = R(\vec{n}_r, \beta_1)\vec{n}_{m0}$.

When the laser beam is reflected by the mirror rotated by β_1 , the normal vector of the laser beam plane will change to $\vec{n}'_1 = \vec{n}_1 - 2\vec{n}_m(\vec{n}_m \cdot \vec{n}_1)$. The normal direction of the left-side laser beam plane \vec{n}'_2 can be also derived in the same way.

After initializing the laser guidance device and fixing the device in the operation space, we can obtain the position of the rotation center (the intersection point of the two motors axes) O_1 and O_2 of each laser beam. The laser beam planes can be determined from the normal direction of the plane and the rotation center as $(X_1 - O_1) \cdot \vec{n}'_1 = 0$, and $(X_2 - O_2) \cdot \vec{n}'_2 = 0$, where X_1 and X_2 are points on the two laser beam planes. The vector of the intersection line of the two laser beam planes is therefore given by $\vec{n} = \vec{n}'_1 \times \vec{n}'_2$.

From the required insertion position and orientation of the laser line determined by the patient-image registration described in next section, we can calculate the rotation angle of the laser shooter and the mirror from the above derivation.

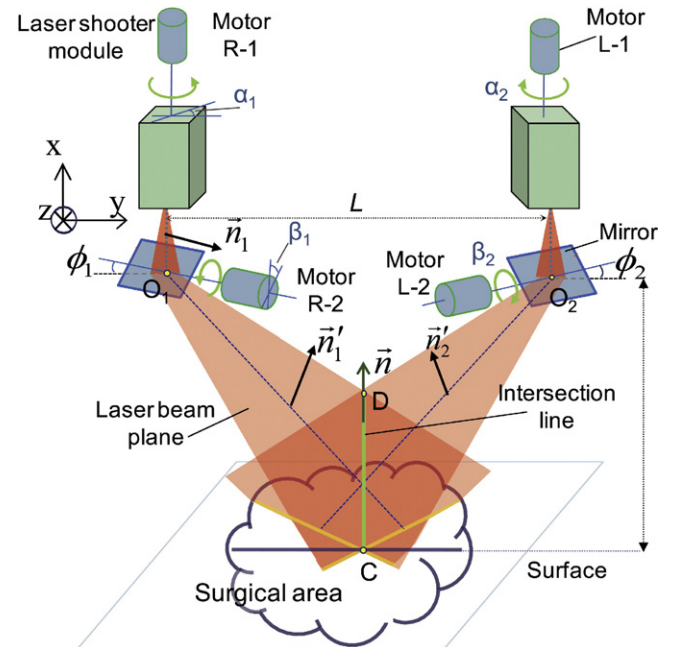


Fig. 5. Calculate rotation angles of motors according to the insertion position and orientation.

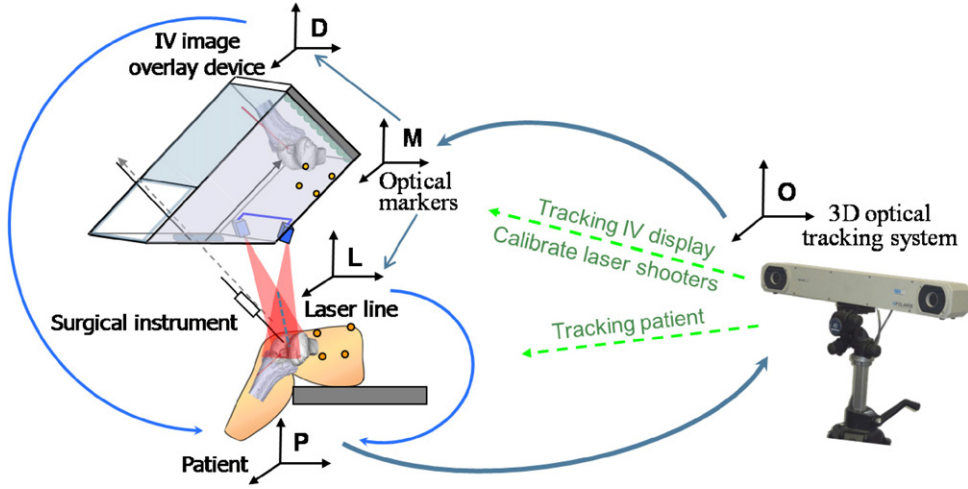


Fig. 6. Geometrical framework for registering laser guidance, IV image overlay, and patient information.

2.5. Combining of laser guidance and IV image overlay

The registration of the surgical navigation system includes the IV image overlay and laser guidance to the anatomical objects. The relationships between coordinates are shown in Fig. 6. Optical markers attached to the overlay device are used for both patient-to-image registration and laser-to-patient registration. To combine the IV image with the line formed by the intersecting laser planes, the calibration and registration process is as follows.

To calibrate the IV image, we relate the position of the IV display and the coordinates of the optical markers, M .

- (1) The calibration of the IV images on the display, D , can be performed by projecting a reference 3D model with calibration points on it and reflecting the IV images into the 3D space via the half-silvered mirror [18]. We calculate the positions of the reflected IV images, producing transformation ${}^D_M T$.
- (2) Calibrate the rigid body of the optical position markers attached to the IV overlay device, relative to the optical tracking system, O , and produce transformation ${}^M_O T$. For this, we can get the relationship between the IV display and the optical tracking system ${}^D_O T = {}^M_O T {}^D_M T$.
Regarding the laser-plane intersection line, since the laser guidance device is fixed to the IV image overlay device, the same optical markers attached to the overlay device give the following transformations:
- (3) Calculate the laser beam planes and corresponding laser line, L , producing transformation ${}^L_M T$.
- (4) Using ${}^M_O T$, get the relationship between the laser line and the optical tracking system: ${}^D_O T = {}^L_M T {}^D_M T$.
- (5) Using the calibration described in Section 2.4, get the relationship between the rotation angle of the motors and the laser line.

For the patient-to-image and patient-to-laser registrations, we use a set of distinct features (geometrical landmarks or natural anatomical landmarks) that can be accurately identified in both the scanned image (CT, MRI, etc.) and the patient's physical space, P , to relate the coordinates of the spaces. Accordingly, the geometric transformations that associate these three spaces (patient, IV image, and laser) can be derived.

- (6) The transformation of the IV image for patient-to-image overlay is given by ${}^D_P T = {}^D_M T {}^M_O T {}^O_P T$, and the laser line for guidance is therefore given by ${}^L_P T = {}^L_M T {}^M_O T {}^O_P T = {}^L_M T ({}^D_M T)^{-1} {}^D_P T$.

After finishing patient-image registration, we drive the motors to rotate the axes of the laser shooter and the mirror to calculated angles. The insertion path for the surgical instrument is along the laser-plane intersection line. The target objects are represented in the form of IVs, which are displayed in real-time on the IV display.

3. Experiments and results

3.1. Laser guidance devices

We fabricated a laser guidance device (Fig. 7) composed of two laser shooters (Edmund, VLMTM 3) and four stepping motors (PK513PA, ORIENTAL MOTOR Co. LTD, Japan), and we mounted it on the bottom of the IV image overlay device. This sort of mount does not influence the implementation of controlling the surgical instrument during the operation. The range of projection angle of the laser beam plane is 30°. The orientation of each laser beam plane is controlled by two motors. One motor rotates the axis of the projected laser beam. The other motor adjusts the reflection angle of the mirror so that the laser plane projects to the surgical field (Fig. 7a). The projected laser beams are illustrated in Fig. 7b. A set of optical tracking markers is attached in the base of the laser guidance device.

3.2. Accuracy of laser guidance

We carried out an experiment to evaluate the accuracy of the laser guidance. We calibrated the laser guidance device with a set of test patterns. The experiment was performed based on the calibration and correction results for the relationship between the motors and laser projection planes. We used the POLARIS optical tracking device to measure the projected crossing point and the intersection line of the two laser beam planes.

The procedure is as follows. We attached an optical tracking sensor to the surgical tool. The position and situation of the surgical tool could be thus obtained by the tracking system. We chose a set of text patterns that included the insertion positions and orientations. For each evaluation, we moved the tool to the required position and orientation and adjusted according to the tracking results of the POLARIS system. We calculated the rotation angles of the laser shooters and the mirrors, and controlled the motors and rotated the two laser beam planes. After finishing the laser beam rotation, we moved the same tool to the crossing point and adjusted the posture of the tool according to laser guidance method described in

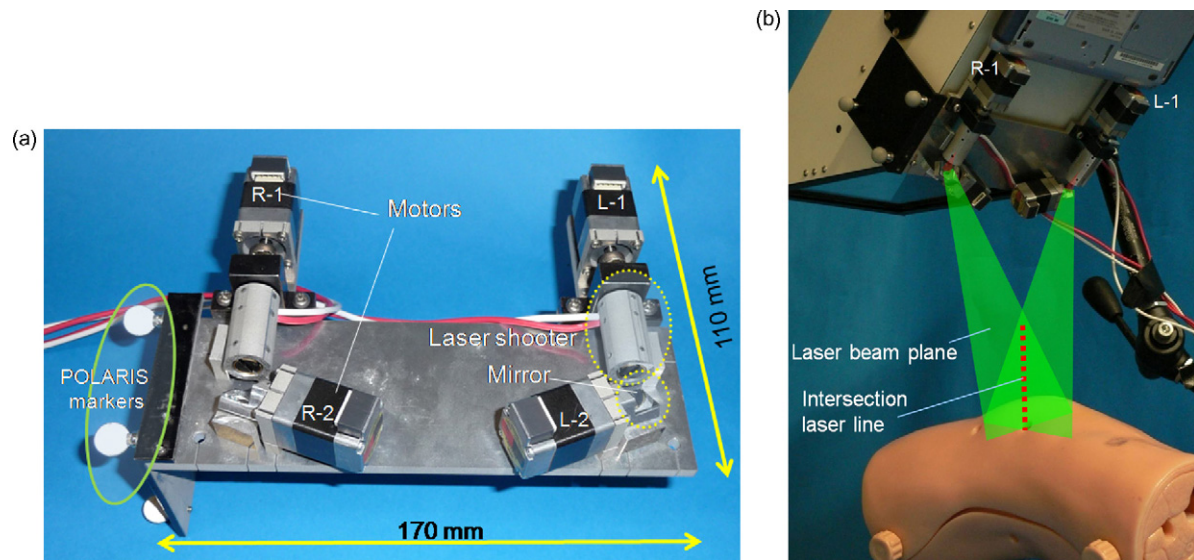


Fig. 7. Laser guidance devices: (a) motors and mirrors for adjusting the orientation of the laser beam planes; (b) laser planes intersect to form a line.

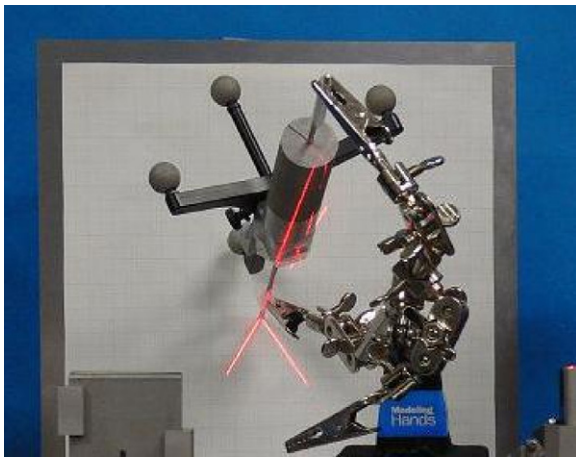


Fig. 8. An optical tracking sensor attached to surgical tool for tracking insertion position and orientation of the tool.

Section 2.1. We measured the position of the crossing point and the orientation of the tool (Fig. 8).

The mean value of the position error of the insertion point for 25 tests was 2.48 mm, and the standard deviation was 1.76 mm. The mean value of the orientation error of the intersection line was 2.96° , and the standard deviation was 2.12° .

We conducted another set of experiments to assess the feasibility of aligning surgical instrument with an insertion path determined by the laser planes (Fig. 9). After deciding the insertion point and orientation, the laser beam planes will be rotated to

Table 1

Main specifications of IV overlay device.

Setup	Specifications	Characteristic
IV display	Size of display	129.0 mm \times 96.7 mm
	Number of pixels	1024 \times 768 pixels
	Pixel pitch	0.127 mm
	Lens pitch	1.001 mm (H), 0.876 mm (V); (hexagon)
	Lens focal length	3.0 mm
	Lens refractive index	Nd = 1.49
Overlay device	Viewing angle	About $\pm 10^\circ$
	Projection distance	300 mm (230 mm–370 mm)
	Weight	2080 g
	Size	175 mm (L) \times 370 mm (W) \times 150 mm (H)
Laser guidance device	Weight	580 g
	Size	170 mm (L) \times 110 mm (W) \times 50 mm (H)
Total device	Weight	2660 g

the calculated directions to intersect and form the guidance laser line. This line makes it easy to guide a surgical instrument.

3.3. IV image overlay

We manufactured an IV image overlay device with a micro-convex lens array, a half-silvered mirror, and a supporting stage (Fig. 10a). The main specifications of the IV display are listed in Table 1. The rendering time of the IV image heavily depended on the complexity of the rendered object. We used a Graphic Processing Unit (GPU)-accelerated IV rendering method to enable

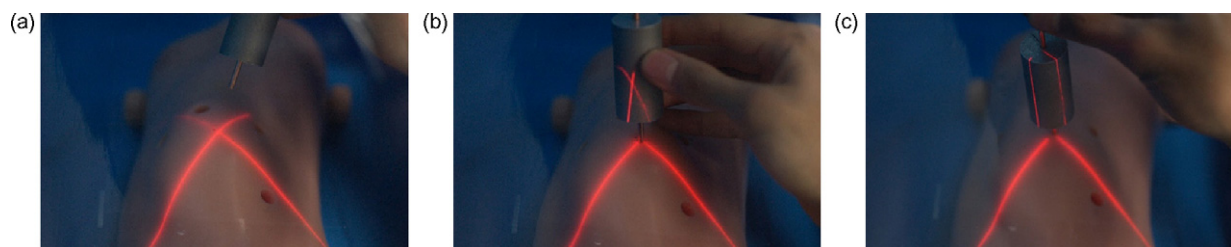


Fig. 9. Alignment of surgical instrument to path determined by laser-plane intersection: (a) move the tip of the surgical instrument to the crossing point of the laser planes; (b) adjust the orientation of the surgical instrument; (c) identify coaxial point and parallel projection lines on the surgical instrument and stabilize the surgical instrument.

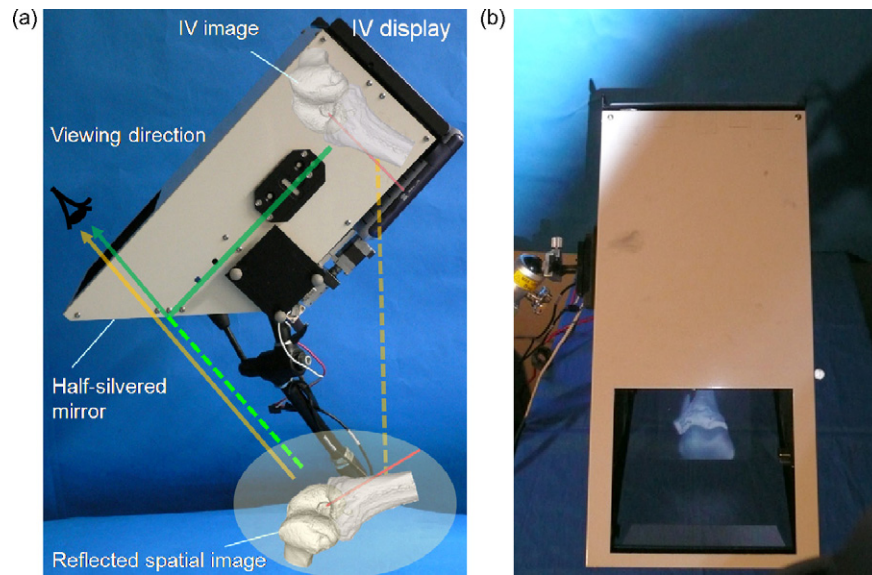


Fig. 10. (a) IV image overlay device; (b) image-overlay result for the knee joints.

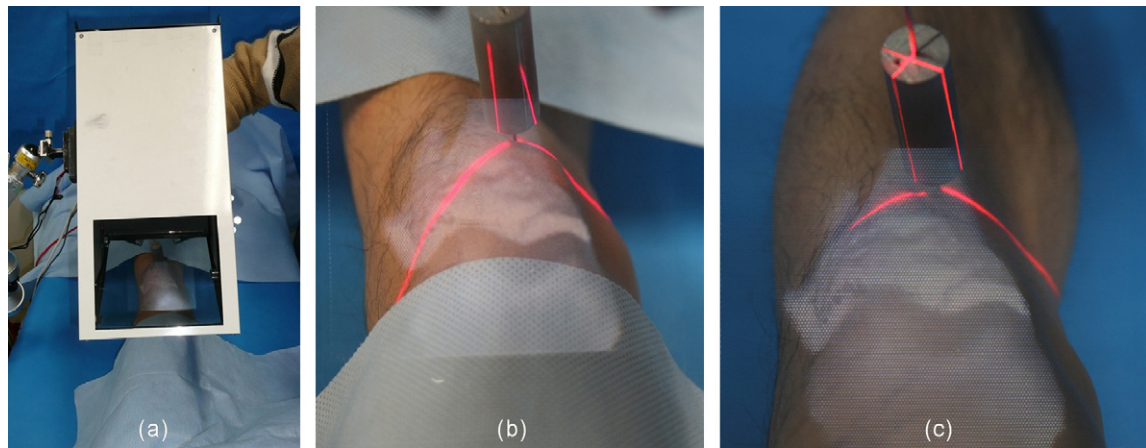


Fig. 11. Example of laser guidance with autostereoscopic image overlay: (a) IV image overlay device and patient with IV image overlay; (b) alignment of surgical instrument; (c) image-patient registration results and surgical path guidance of laser beams.

real-time IV rendering. Despite the complexity of the data, the method enabled an update speed of 14 frames per second for a data of $256 \times 256 \times 256$ voxels worth of data (on an Intel Pentium 4, 3.2 GHz CPU). The IV image could be calculated and displayed in almost real-time with our optimized algorithm.

The IV image could be superimposed onto the patient with fiducial marker based registration. Once all objects to be displayed are transformed into the same coordinate space, they appear to the surgeon exactly as if they were in their actual spatial locations. One of the overlaid IV images is shown in Fig. 10b.



Fig. 12. (a) Observe the surgical instrument aligned with the intersected laser line from side. (b) Observe from the viewing windows of the IV image overlay device.

3.4. Feasibility study of IV image overlay and laser guidance system

A volunteer trial was undertaken to evaluate the feasibility of the system. The feasibility study was approved by the ethics committee of the university. We performed CT scans of a human knee. The volumetric CT images for the knee (512×512 pixels \times 347 slices, thickness of 0.5 mm) were segmented, and the results were rendered and transmitted to the IV display. We integrated the IV segmentation image in a simulated knee surgery and superimposed the IV image on the actual position (Fig. 11a). The position of the insertion point and the orientation of the intersection line were calculated, and the laser planes were adjusted by rotating the motors. Fig. 11b shows the procedure of alignment of the surgical instrument, and Fig. 11c shows the image-patient registration results. We could align the surgical instrument with the laser beam planes intersected laser line from the side of the device (Fig. 12a) or from the viewing window of the IV image overlay device (Fig. 12b). The feasibility study showed that the system provided both intuitive 3D information about the anatomical structure of the organ and guidance for the surgical instrument.

4. Discussion and conclusion

We developed a surgical navigation system that combines an autostereoscopic image overlay technique with a laser guidance technique. An actual 3D image is superimposed onto the patient by using a semi-transparent display based on integral videography. The laser guidance technique is used to show the insertion path of a linear surgical instrument. Experimental findings indicated the feasibility of the system with the laser guidance technique and IV image overlay technique. The accuracy of laser guidance was 2.48 mm on average. Although the accuracy does not quite meet the requirement for the orthopedic surgery (less than 1 mm), with improvement and further evaluation, the system may become satisfactory for precision-guided knee joint surgery. The orientation error was 2.96° , and the standard deviation was 2.12° . The precisions of the laser shooter and motors can be increased to reduce these figures to an acceptable level for orthopedic surgery. It will then be possible to register an anatomical object's configuration with an intra-operative surgical instrument with high precision through real-time IV image rendering. Moreover, for soft tissue or deformable tissue around the bone, the patient-IV image registration should be corrected by sensing intra-operative tissue images and automatically updating the displayed image. One of the solutions is to fix optical markers to the bone and calculate the thickness of the soft tissue from the scanned images. The position of the crossing point and the orientation of the guidance laser line can be corrected to fit the shape of the soft tissues.

The viewing areas of the image overlay and laser guidance were limited. If we want to change the observed area, the device must be moved and rotated. Fortunately, the optical markers attached to the overlay device can be used for tracking the position and orientation of the device, and the IV images can be updated. Furthermore, the projected direction of the laser beam could be automatically changed to correspond to the position and orientation of the overlay device.

The guidance area of the laser should be enlarged and the projected laser beam planes should be mounted on a long arm so that the laser-plane intersection line can be controlled over a wider area. More driven devices for rotation or translation should be installed to increase degrees of freedom of the laser beam planes. The freedom of Moreover, one laser line can provide guidance for only one surgical tool. Guidance for multiple targets and surgical instruments might be able to be provided by using multiple laser shooters or multiple planes laser projectors. The thickness of the intersected

laser lines relative to their orientation to the skin surface should be considered, although the change is small because the guidance area is small.

In conclusion, our precision-guided surgical navigation system can superimpose a real 3D image onto a patient's body for accurate and less-invasive surgery and intuitive guidance of a linear surgical instrument. Experimental results show that this precision-guided system can support surgeons during their operations. Our system is simple and it quickly provide an intra-operative information about the anatomical structure. It enables the surgeons to identify the insertion path of the surgical instrument intuitively. We believe that the accuracy of real-time projected point location can be improved by using a display device with a higher pixel density and a laser guidance device with higher precision; hence, this system should be of practical use in orthopedic surgery and other medical applications.

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